Disk-Outflow system around spinning black holes and explaining the observed FSRQ-BL Lac dichotomy

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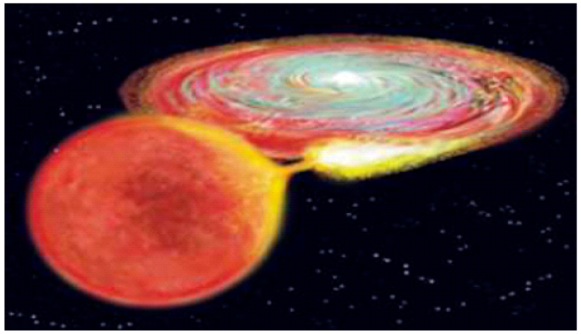
Motivation

- Jets/Outflows in astrophysics: AGNs, microquasars
- Origin of jets is still not well understood
- They are coming from disk and thus the base of jet cannot be treated independent of disk.
- Does the spin of black hole play any role in forming jet? Not explored much
- By spin we mean specific angular momentum of the black hole: varies 0 – 1 (proposed by Kerr 1963)

Accretion models

- Geometrically thin, optically thick Keplerian disk : $Q^+ = Q^-$

  Flow is radiation pressure dominated; spectrum → soft/ultra-soft blackbody (hv~100 eV - 10keV) - standard disk model (Shakura & Sunayev 1973, Novikov & Thorne 1973).



- Two temperature disk: hot, gas pressure dominated, optically thin; spectrum→ hard X-rays (hv~10 KeV - 500 KeV).

  Explains Cyg X-1

  (hv~100 keV; Shapiro, Lightman & Eardley 1976).
- Geometrically thick disk model: supercritical accretion flow, strongly radiation dominated, non-Keplerian, optically thick → Explains high/ultra high luminosity: e.g. SS433 (Abramowicz, Calvani & Nobili 1980).
- Modern advective disk: substantially sub-Keplerian, advective, gometrically thick, optically thin disk (e.g. Narayan & Yi 1995, Chakrabarti 1996, Rajesh & Mukhopadhyay 2010).

  Extreme case: ADAF ($f \to 1$), inefficient cooling, optically thin, highly subcritical gas pressure dominated (Narayan & Yi 1994): e.g. Sagittarius A^*

Outflows/Jets

- ☐ Galactic & Extragalactic jets formed in the vicinity of rotating black holes, e.g. microquasars (GRS 1915+105).
- ☐ Outflows/jets are manifestations of accretion disk→ extract matter, energy and angular momentum.
- ☐ No unique/standard models for outflow/jet.
- ☐ Most models treat apparently disk flow and outflow as dissimilar objects. Famous models: electrodynamically accelerated model (Blandford & Znajek mechansim), self-similar magnetically and centrifugally driven outflows (Blandford & Payne 1982, Lovelace et al. 1986).
- ☐ Simulations of jet (de Villers, Hawley 2003; Mckinney & Gammie 2004).
- ☐ Disk-outflow/jet are correlated: correlation of radio/X-ray emission (Fender et al 2005; Rawlings & Saunders 1991).
- ☐ Jets observed at low/hard state → emanate from strongly advective region (ADAF solutions, ULXs, CENBOL).
- ☐ Outflows/jets are more powerful for highly subcritical & supercritical flows.

2.5-dimensional disk-outflow model

- ❖ We consider the correlated dynamics governed by conservation laws
- ❖ This is based on "Bi-directional" hypothesis: outflow/jet is necessary to satisfy disk boundary condition

New Insights:

- We solve complete set of coupled partial differential hydrodynamic equations in the advective regime from first principle.
- We consider variation of flow parameters in both r & z direction.
- We incorporate explicitly the outflow velocity in the relevant fluid equations.
- We do not assume hydrostatic equilibrium.

Assumptions:

- Magnetic field neglected→ aim at understanding spin influence solely
  → no aspiration to describe jet mechanism

Supercritical accretion: outflow/jet ejected, accelerated & collimated by strong radiation pressure (e.g. Abramowicz & Piran 1980)

- Viscous effect neglected → a predefined region of inner accretion disk

Model equations in pseudo-Newtonian approach

Mass transfer:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r) + \frac{\partial}{\partial z}(\rho v_z) = 0, \qquad \frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r) + \frac{\rho v_z}{z} = 0.$$

Radial momentum balance:

$$v_r\frac{\partial v_r}{\partial r} + v_z\frac{\partial v_r}{\partial z} - \frac{\lambda^2}{r^3} + F_{Gr} + \frac{1}{\rho}\frac{\partial P}{\partial r} = 0,$$

$$v_r\frac{\partial v_r}{\partial r} + v_z\frac{v_r - v_{r0}}{z} - \frac{\lambda^2}{r^3} + F_{Gr} + \frac{1}{\rho}\frac{\partial P}{\partial r} = 0$$

Angular momentum balance:

$\lambda_{disk} + \lambda_{outflow}$ = Constant

Vertical momentum balance:

$$v_r\frac{\partial v_z}{\partial r} + v_z\frac{\partial v_z}{\partial z} + F_{Gz} + \frac{1}{\rho}\frac{\partial P}{\partial z} = 0,$$

$$v_r\frac{\partial v_z}{\partial r} + \frac{v_z^2}{z} + F_{Gz} + \frac{1}{\rho}\frac{P - P_0}{z} = 0$$

Bhattacharya, Ghosh & Mukhopadhyay ApJ 2010

Force corresponding to pseudo-Newtonian potential

- GR effects mimicked by pseudo-Newtonian approach: A methodology adopted by Mukhopadhyay (2002).
- Disk-outflow/jet coupled system → Generalized Kerr potential:

$$F_{K\rho} = \frac{2\mathcal{A}^2\mathcal{B}^{-1/2}}{\left[a\sqrt{2}\rho^{3/2}\mathcal{B}^{1/4}\{\Delta + 2\rho\mathcal{B}^{1/2}(\rho\mathcal{B}^{1/2} - 1)\} + \Delta\sqrt{\rho^2 - z^2}\,\{\mathcal{A} + \rho^4\mathcal{B}^2 - a^2(\Delta + \rho^2\mathcal{B} - 3\rho\mathcal{B}^{1/2})\}^{1/2}\right]^2}$$

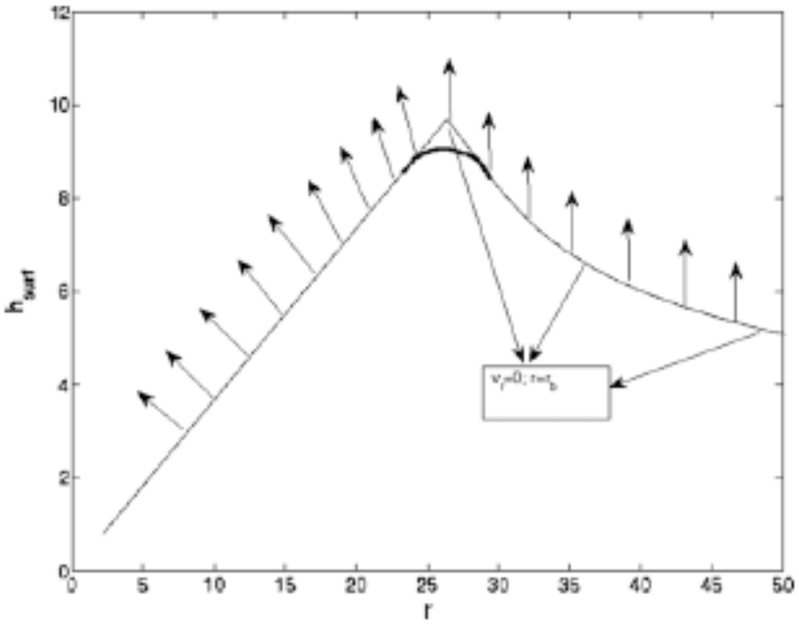
$$F_{Kz} = \frac{2\mathcal{A}^2\mathcal{B}^{-1/2}z}{\left[a\sqrt{2}\rho^2\mathcal{B}^{1/4}\{\Delta + 2\rho\mathcal{B}^{1/2}(\rho\mathcal{B}^{1/2} - 1)\} + \Delta\rho^{1/2}\sqrt{\rho^2 - z^2}\,\{\mathcal{A} + \rho^4\mathcal{B}^2 - a^2(\Delta + \rho^2\mathcal{B} - 3\rho\mathcal{B}^{1/2})\}^{1/2}\right]^2}$$

$$\mathcal{B} = 1 + z^2/\rho^2,\ \Delta = \rho^2\mathcal{B} - 2M\rho\mathcal{B}^{1/2} + a^2,\ \mathcal{A} = a^4 + \rho^4\mathcal{B}^2 + 2a^2\rho\mathcal{B}^{1/2}(\rho\mathcal{B}^{1/2} - 2)$$

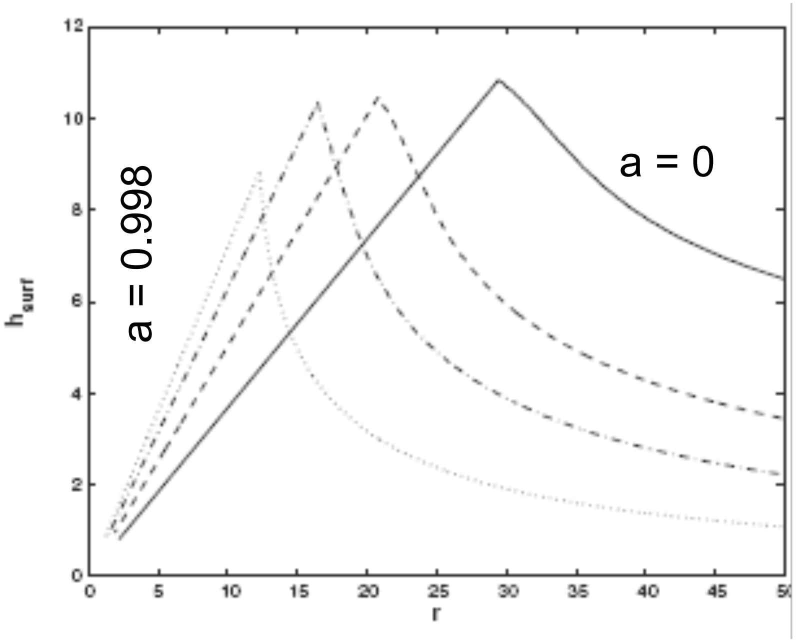
Ghosh & Mukhopadhyay ApJ 2007

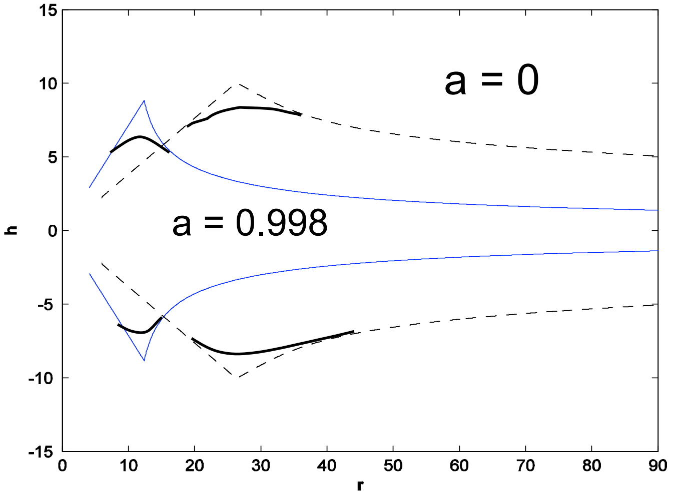
Zero v_r surface: height

velocity across outflow surface



outflow surface for various spin





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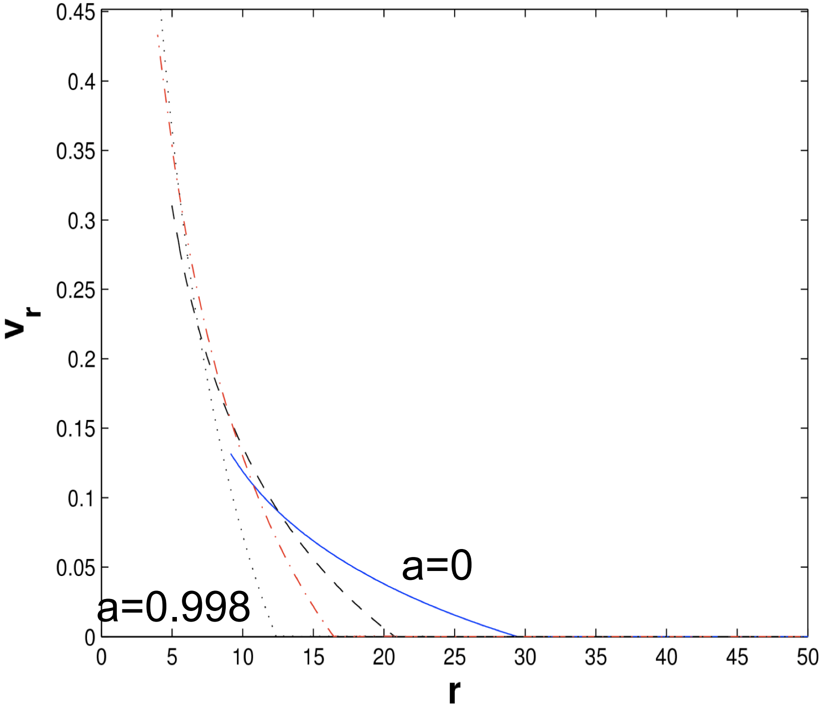
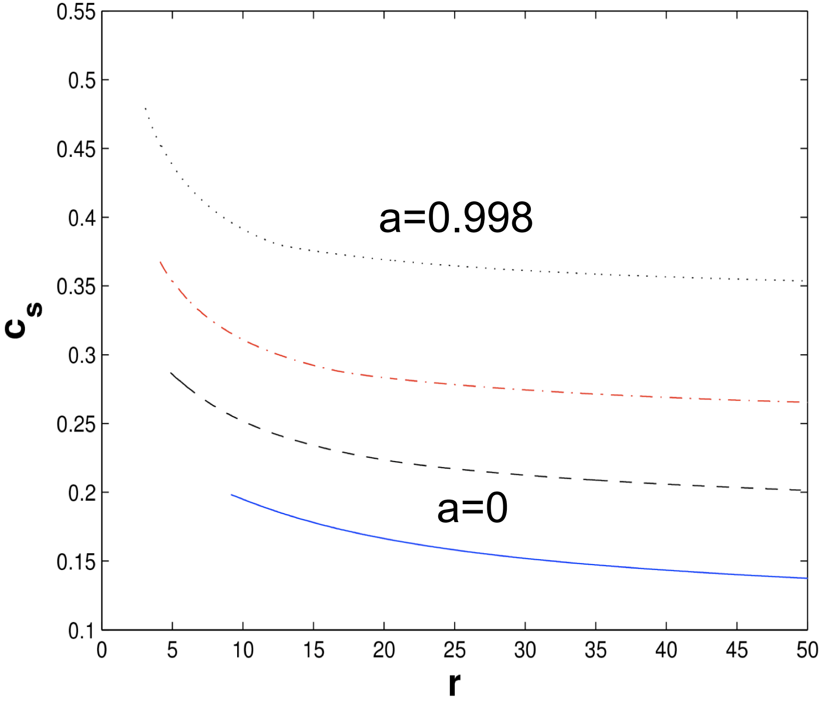
Radial Velocity for different spin



Sound speed for different spin



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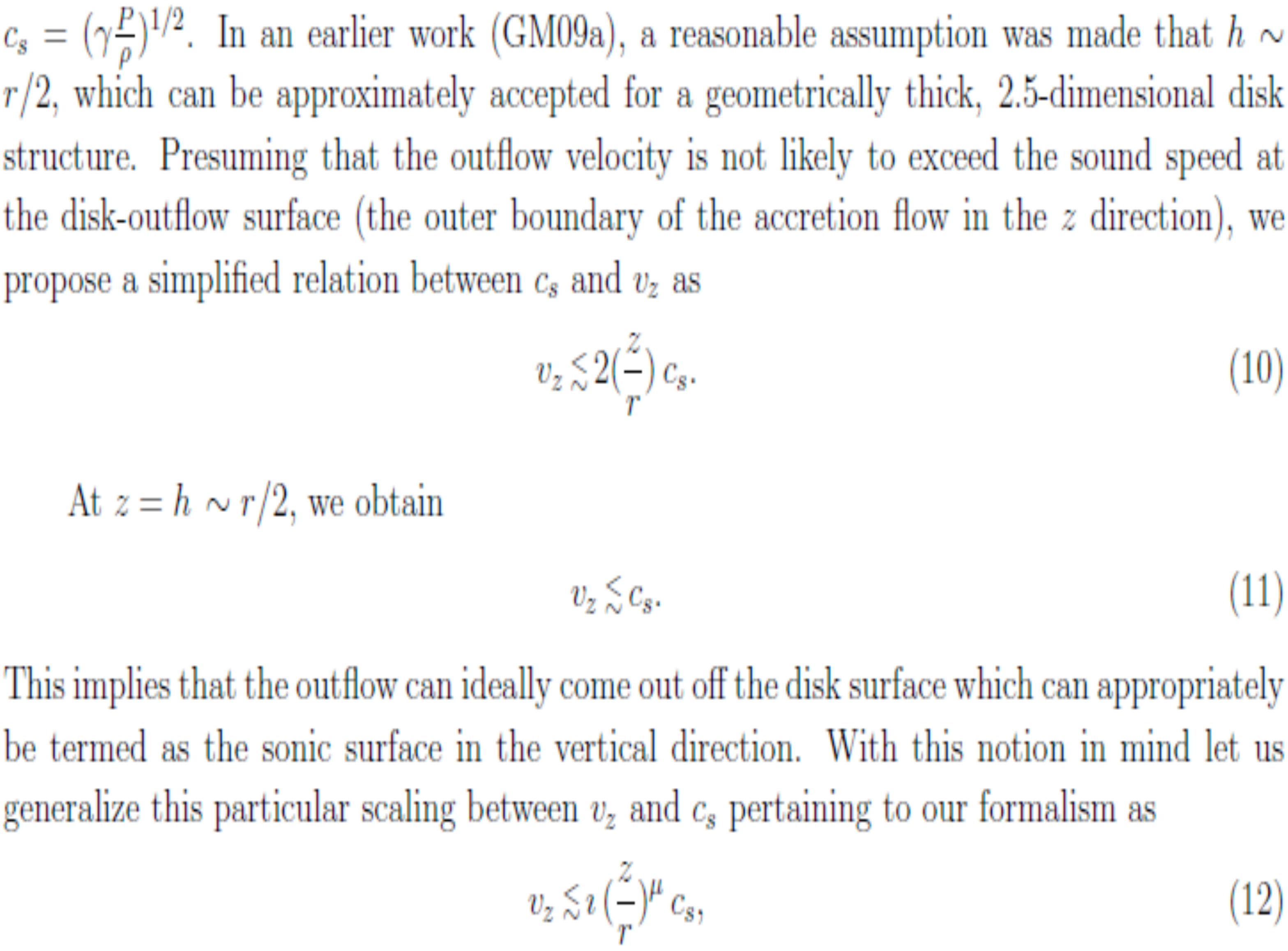


$c_s = (\gamma \frac{P}{\rho})^{1/2}$. In an earlier work (GM09a), a reasonable assumption was made that $h \sim r/2$, which can be approximately accepted for a geometrically thick, 2.5-dimensional disk structure. Presuming that the outflow velocity is not likely to exceed the sound speed at the disk-outflow surface (the outer boundary of the accretion flow in the z direction), we propose a simplified relation between c_s and v_z as

$$v_z \lesssim 2(\frac{z}{r})\, c_s. \qquad (10)$$

At $z = h \sim r/2$, we obtain

$$v_z \lesssim c_s. \qquad (11)$$

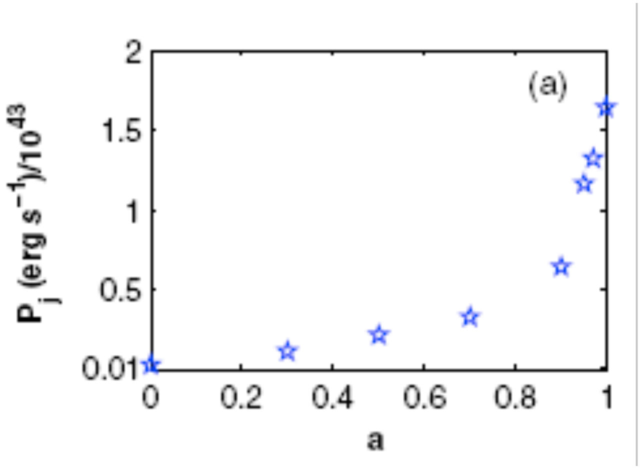
This implies that the outflow can ideally come out off the disk surface which can appropriately be termed as the sonic surface in the vertical direction. With this notion in mind let us generalize this particular scaling between v_z and c_s pertaining to our formalism as

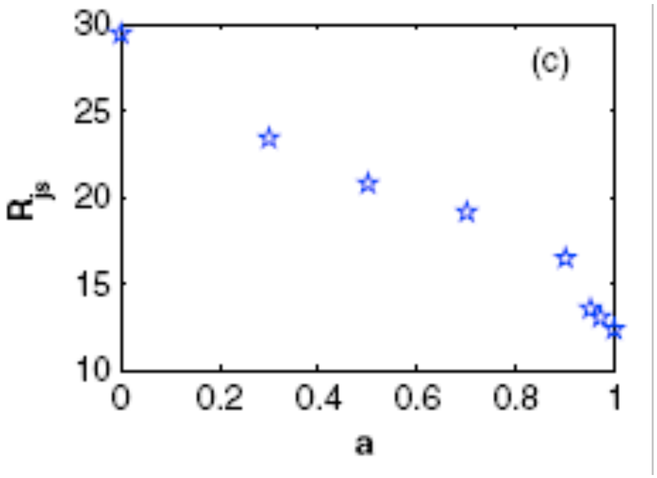
$$v_z \lesssim \imath\, (\frac{z}{r})^{\mu}\, c_s, \qquad (12)$$

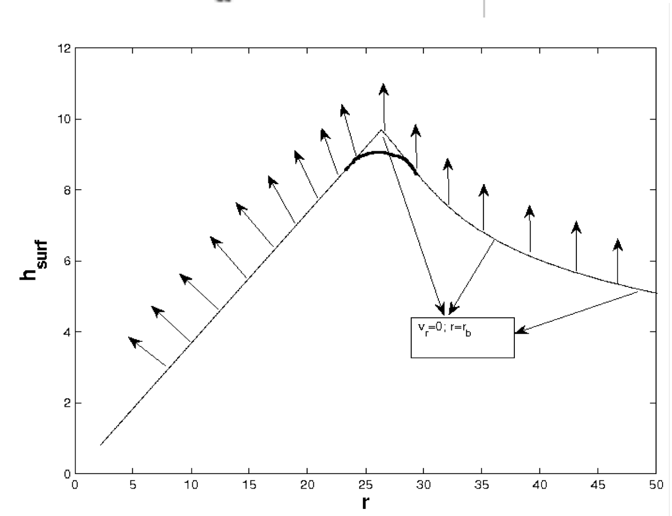
Ghosh & Mukhopadhyay RAA 2009
Bhattacharya, Ghosh & Mukhopadhyay ApJ 2010

$M=10^8 M_{sun}$, Accretion rate=0.01 Eddington unit

$$P_j(r) = \int 4\pi r \left[\left(\frac{v^2}{2} + \frac{\gamma}{\gamma-1}\frac{P}{\rho} + \phi_G \right) \rho v_z \right] \Big|_{h_{\rm surf}} dr,$$







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Blazars

Significant difference in luminosities among different classes of AGNs

Jet to line-of-sight angle is small

FSRQs

High luminous

Steep spectra in High energy (average γ-ray photon sp. Index ~ 2.4)

Ghisellini et al. (2009) agued the luminosity difference is due to difference in accretion rate

BL Lacs

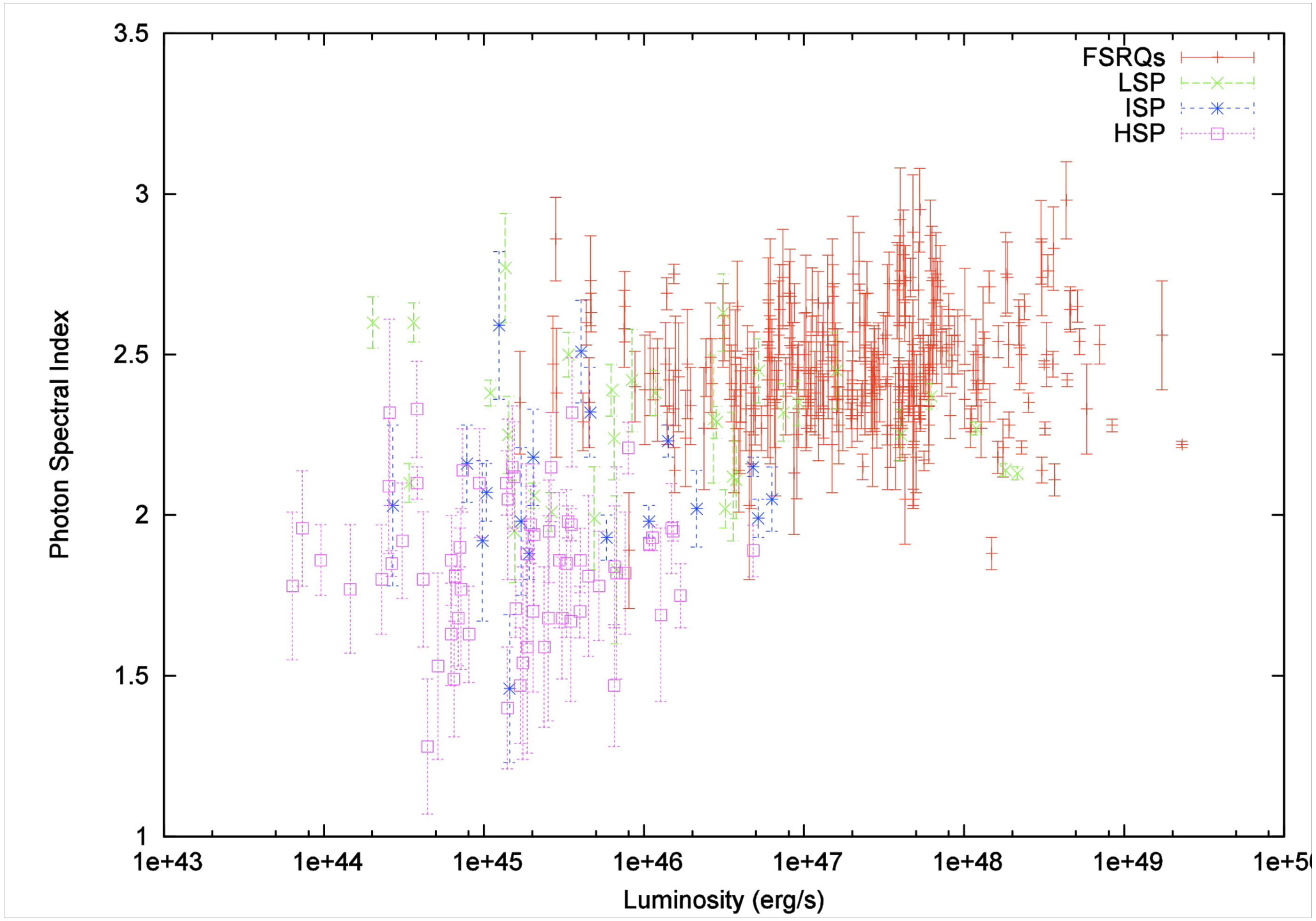
Relatively low luminous (almost 3 order less)

Flat spectra in High energy (average γ-ray photon sp. Index ~ 2)

- ❖ See poster P27 by Debbijoy Bhattacharya based on Fermi data
- ❖ See: P04 (B. Karak), P09 (M.C. Ramadevi), P16 (R. Mallick)

  - ➢ By MHD simulation Tchekhovskoy, Narayan & Mckinney (2010) explained radio loud/quiet dichotomy of AGNs based on spin difference

- 11 months Fermi data (Abdo et al. 2010) :
- 281 FSRQs, 291 BL Lacs (121 with measured z)



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Radio observations (Savolainen et al. 2010)

- Average Doppler beaming factor (δ) :
- $\delta = 1/[\Gamma(1 - \beta \cos\theta)]$, Γ → bulk Lorentz factor

- For FSRQs : ~ 15
- For BL Lacs: ~ 8

- $L_{observed} = L_{intrinsic} \times \delta^{(m+n)}$ (Dermer 1995)

  m=2 for continuous jet, m=3 discrete jet

  $n=\alpha_\gamma$ for SSC process, $n=2\alpha_\gamma+1$ for EC process

  α_γ=energy spectral index

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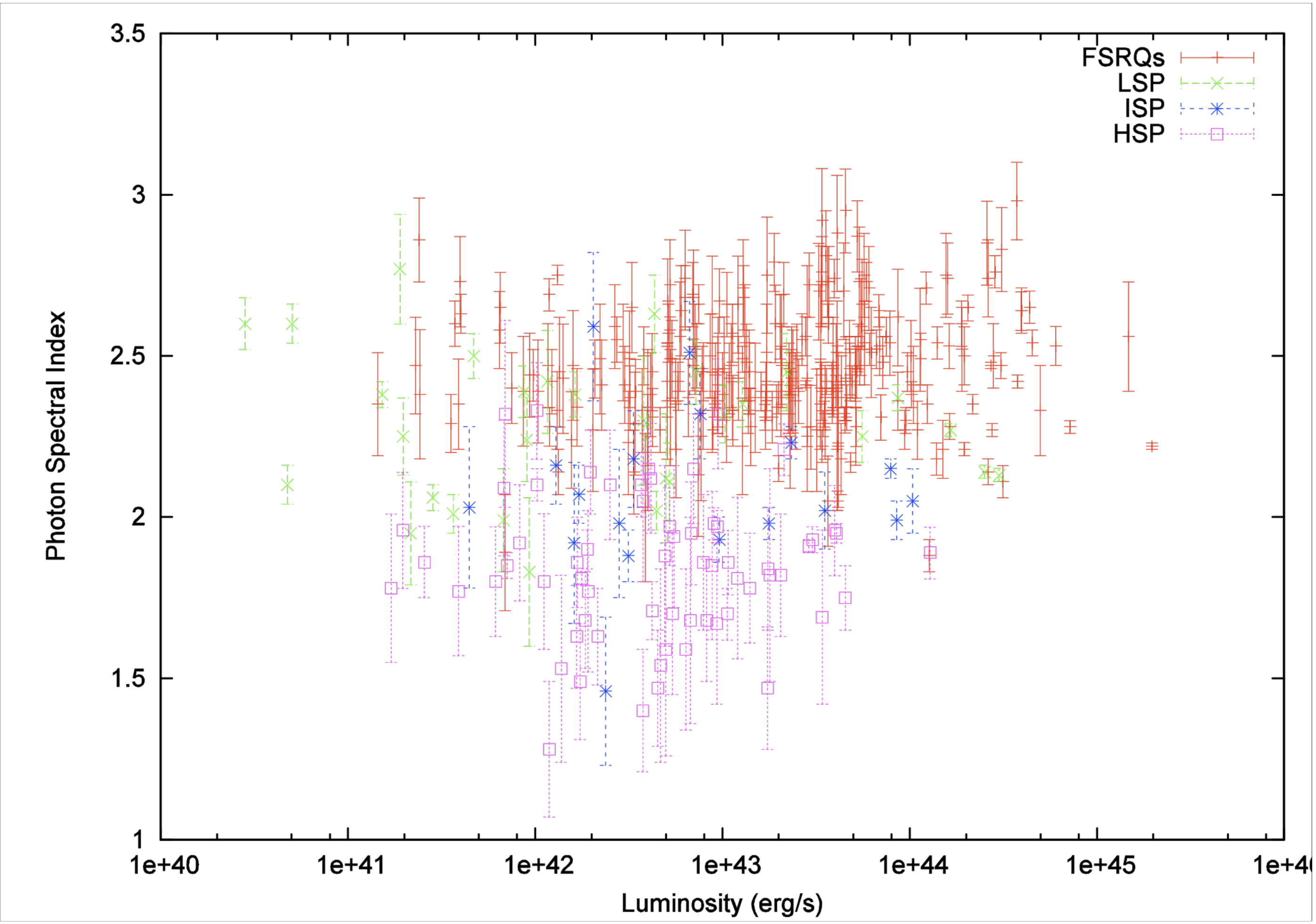
Intrinsic luminosity (luminosity corrected for Dopper beaming)

$L_{\mathrm{intrinsic}}$



- ✓ Small difference in intrinsic luminosity may not be due to huge difference in accretion rate
- ✓ Huge difference in observed luminosity must arise from the spin of black hole controlling velocity and Doppler effect

See Poster P27 by Debbijoy Bhattacharya

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Summary

- ✓ We model accretion-outflow under same platform, based on basic laws of conservation.
- ✓ Interestingly more power and then more luminosity is for rapidly spinning black holes.
- ✓ Among high luminous AGNs, however, observationally FSRQs are more luminous than BL Lacs, while the corresponding intrinsic luminosities do not differ much ----- FSRQs might be highly spinning black hole sources exhibiting higher Lorentz factors and Doppler effects.
- ✓ In future magnetic field and detailed radiative processes should be included to make the model more global.